ARMY RESEARCH LABORATORY

Physical Characteristics of Fire-Extinguishing Powders

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Physical Characteristics of Fire-Extinguishing Powders

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Abstract

Powders are known to be highly efficient fire-extinguishing agents. There are powders available that, on both weight and volume bases, are more efficient than Halon 1301 as fire-extinguishing agents. A project was undertaken to examine several powders by both optical microscopy and scanning election microscopy. Much of the information from these two forms of microscopy is complementary.

The term "characteristic dimension" was defined and applied in order to rank the powders on a size basis. Eleven fire-extinguishing powders and two common commercial powders were examined by both forms of microscopy. The fire-extinguishing grade of aluminum oxide had the smallest average characteristic dimension followed by the "micronized" sodium bicarbonate samples. These sodium bicarbonate powders appeared to have very little agglomeration of the particles. The large amount of drying agent (approximately 8%) may explain this fact. In addition, most of the sodium bicarbonate powders had similar average characteristic dimensions. Therefore, it is felt that they may perform similarly as fire-extinguishing agents.

Preface

Many finely divided solids (nonflammable salts) have been used to quench hydrocarbon flames. Sodium bicarbonate was widely used into the 1950s as the primary fire-extinguishing powder. The U.S. Navy determined that potassium bicarbonate was superior to the sodium analog, and subsequently changed its hand-held extinguishers from sodium bicarbonate to potassium bicarbonate. Other solids, such as Monnex, have been proposed, but their fire-extinguishing ability is only marginally superior to the potassium bicarbonate. Because of the expense, there has been resistance to a changeover.

It is widely believed that fire-extinguishing powders can function as both energy-absorbing materials and as solid surfaces on which free radicals can be destroyed (Finnerty and Vande Kieft 1996). Heat may be absorbed by the heat capacity of the solid, the heat of fusion at the melting point, the heat capacity of the liquid, heat of dissociation from breaking of chemical bonds, and heat of vaporization. These all contribute to the total endothermicity of the fire-extinguishing powder (Ewing 1984).

From a chemical aspect (Dolan 1956; Altman et al. 1983), it has been found that potassium salts are more effective than sodium salts, and iodide anions are more effective than chloride anions. Presumably, there is a catalytic path for destruction of free radicals, such as H, O, and OH, utilizing the potassium in the salts. It must be remembered that any powder that has a chemical fire-extinguishing capability will also have a heat-absorbing (endothermic) capability (Finnerty and Vande Kieft 1997).

Ewing (1984) has shown that less weight of salt per unit volume of a fuel-air mixture is required for extinguishment if the salt is finely divided. Large particles may actually pass through the flame zone before they can reach flame temperature, and thus not absorb as much heat as an equivalent mass of finer particles. Another way to look at it is that the time required for small particles to become effective is less than that for large particles. Thus, micrometer-sized solids are more

efficient as fire-extinguishing powders than are larger particles. Large surface areas are important in both the heat absorption and the chemical interference mechanisms.

Acknowledgments

The authors are grateful for the financial support and continued consultation and encouragement from Messrs. Steve McCormack and Mike Clausson of U.S. Army Tank Automotive Research, Development, and Engineering Center (TARDEC), Warren, MI. The U.S. Army is also indebted to them for their zeal and dedication to the search for and identification of appropriate substitute materials for Halon 1301 as a fire-extinguishing agent.

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1. Introduction

One of the motivating factors in this study was the establishment of the Montreal Protocol of 1986 and its amendments. This protocol has forbidden the manufacture of Halon 1301 since 1 January 1994. Since the United States is a signatory to this accord, the Army must prepare for the day when Halon is no longer available for use.

In many cases, there is a hesitation to use conventional fire-extinguishing powders such as Purple K, Monnex, and sodium bicarbonate, which can be corrosive to metals, especially aluminum. Therefore, aluminum oxide powder, which is chemically unreactive, has been chosen for aircraft applications. This material has no ability to melt or vaporize or undergo bond breaking at the temperatures encountered in hydrocarbon flames. Yet tests have shown that aluminum oxide powder is effective in extinguishing fires even though it has only the heat capacity of the solid to serve as its heat sink. This fact prompted a decision to examine aluminum oxide powder in a scanning electron microscope (SEM) to determine if there was anything unusual about this material.

This in turn led to a decision to examine new types of micronized sodium bicarbonate powders that have recently become commercially available. These powders have been proposed for use in engine compartments of combat vehicles. In order to complete this study, other common fire-extinguishing powders have also been examined. Since the expense of full-scale testing of all the powders under consideration would have been prohibitive, a simple method of screening these powders for their effectiveness as fire-extinguishing agents was needed. From the physics of fire extinguishment, the following parameters were selected: particle size distribution, degree of agglomeration, and appearance (amorphous or crystalline). The materials that were evaluated are all currently accepted fire-extinguishing agents, and therefore possess the quality, in various degrees, of endothermicity; obviously, they are also acceptable from the standpoint of toxicity. Interpretation of SEM and optical microscopy photographs was employed as the screening method in this study.

Obviously, powder fire-extinguishing agents are not suitable for use in occupied (crew) spaces; however, they may find utility in unoccupied compartments, e.g., engine compartments. Even in this application, toxicity is of concern, and only recognized fire-extinguishing agents would be applicable.

2. Description of Experiments

2.1 Samples. Thirteen types of fire-extinguishing powders were available for testing. Eight were samples of sodium bicarbonate from various manufacturers. Table 1 gives some details about the powders that were evaluated.

2.2. Sample Preparation for SEM Observation. Powder samples arrived in variously sized and shaped containers. A uniform distribution of physical characteristics—including particle size, shape, and morphology—was assumed. The instrument used was an International Scientific Instruments (ISI) model Super III-A SEM. One-half-inch by one-half-inch cylindrical aluminum pedestals are used in this instrument for sample mounting. A small piece of double-sticky tape was placed on the upper flat surface to accept the sample powder. The powder was lightly stirred to bring some of it up from beneath the surface, to promote more representative sample selection, and a small spatula was used to extract a very small amount of powder from the container. The spatula was held a few centimeters above the pedestal, and gently tapped until the desired amount of powder had fallen onto the pedestal. The pedestal was in turn tapped in various places to distribute the powder more uniformly over the surface area. The sample was then sputtered with a gold-palladium alloy for 2 min at 15 μA current and 75 μmHg pressure to ensure uniform conductivity and to prevent sample charging during exposure to the electron beam. The sample, prepared in this manner, was then inserted into the SEM sample holder, and photographed at several magnifications. Operator bias can enter the procedure here in the choice of sample region to study and analyze; therefore, the two methods, SEM and optical microscopy, were employed.

Table 1. Listing of Samples That Were Investigated

Powder	Description	Source
Amerex	Sodium Bicarbonate	Aberdeen Test Center (ATC)
Ansul + 50	Sodium Bicarbonate	ATC
Ansul + 50C	Sodium Bicarbonate	ATC
Arm and Hammer	Sodium Bicarbonate	K-Mart
Desicarb Regular	Sodium Bicarbonate	ATC
DXP Clone Desicarb	Sodium Bicarbonate	ATC
Kidde	Sodium Bicarbonate	ATC
BSC Siliconized	Sodium Bicarbonate	ATC
Aluminum Oxide (Al_2O_3)	Fire-Extinguishing Grade	Alcoa Composites
Al_2O_3	Anhydrous	Phaltz and Bauer
MAP	Monoammonium Phosphate	Local Fire Department
Monnex	Condensation product of urea and potassium bicarbonate ($KHCO_3$) plus 15% excess $KHCO_3$	ICI
Purple K	$KHCO_3$ plus a purple dye	Automated Protection Systems

2.3 Sample Preparation for Optical Microscopy. Optical photomicroscopy was also done on all of the aforementioned samples, using a Nikon Optiphot binocular optical microscope. The microscope slides were cleaned and then coated with a very thin film of silicone grease. The grease was necessary to keep the powder in place on the slides during handling and observation. A small quantity, approximately 1 g of the powder as received, was placed into an evaporating dish and a stream of air directed onto it from an atomizing squeeze bulb. The aerosolized powder was allowed to fall onto the microscope slide. Care was taken to ensure that the microscope slide was approximately in the center of the footprint of the falling powder. To avoid observational bias, each slide was observed in the microscope at the same five coordinate locations (Figure 1).

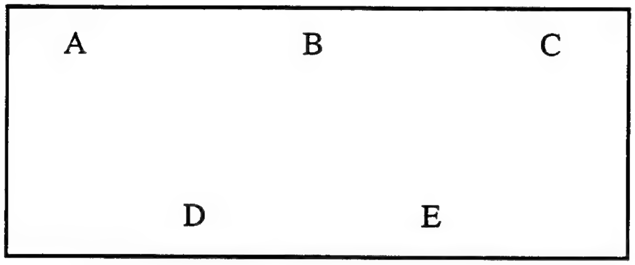

Figure 1. Coordinate Locations Used for Optical Microscope Observations.

The method of obtaining samples for SEM observation was considered to produce valid representations of particle size distributions, whereas the aerosolization method used to make samples for optical microscopy may not have produced samples that were as independent of particle size. However, the authors think that valid samples, with care and practice, were obtained.

2.4 Assessment Criteria for SEM Samples. Several characteristics are relevant to the evaluation of powders as potential fire-extinguishing agents. Those used in this study are the following: size in two dimensions of the median particle and of the largest and smallest particle found; particle size distribution; degree of agglomeration; appearance; and, for certain samples, surface texture.

2.5 Assessment Criteria for Optical Samples. Particle-size distribution and both average and median particle sizes were used to predict the effectiveness of the powders as fire-extinguishing agents. Photographs of each slide were taken at the five predetermined positions. Particle size was determined as follows. All particles except "dust"* were treated as two-dimensional rectangular particles. A photograph of a calibrated scale with 10-μm subdivisions was used for size reference. Each particle (above the arbitrary cutoff of 7 μm for the largest dimension) was measured for the maximum dimension and its corresponding dimension, 90° from the maximum (treated as a rectangle). The calculated area of each particle was determined by multiplying the two dimensions.

* "Dust" was defined as any particle whose largest dimension was less than 7 μm. This screen was used only for optical samples. The dust was excluded because the aerosolizing technique suspended the fine particles more efficiently than the larger particles. It was thought that the smaller particles were overrepresented on the microscope slide collectors.

The square root of this "area" was taken and called the "characteristic dimension" of the particle. The areas were used to calculate the average and median particle sizes at each of the five locations on each slide. The characteristic dimension of the particle was used as a measure of the size of the fire-extinguishing powder. The particle-size distribution was used as an indication of the quality control during manufacture and packaging/distribution.

3. Results

3.1 SEM. The SEM photographs were analyzed for what appeared to the analyst to be the largest, smallest, and median size particles. Appearance and surface texture were also observed and recorded. Table 2 presents these data for the 13 powders analyzed. A representative SEM photograph is shown in Figure 2.

3.2 Optical Microscopy. Each of the 13 materials was observed and analyzed at the five predetermined positions. The measurements of collected particles of the 13 powders are presented in Tables A-1 to A-13 of the Appendix inclusively and are summarized in Table 3. There was very little overlap of particles in the photographs of each position. Data on average and median particle sizes of concern, when these powders are used as fire-extinguishing agents, are presented in Table 3. Appropriate comments and observations on degree of agglomeration are included. A representative photograph of an optical microscopy photograph is shown in Figure 3.

The largest particle found on each of the 13 slides is also reported in Table 3. The BSC siliconized sodium bicarbonate had the largest particle found, with a characteristic dimension of 132 μm. There were no other particles of BSC material with a characteristic dimension above 73.6 μm. It is felt that the one very large particle is an anomaly, not representative of the BSC siliconized sodium bicarbonate sample. The Purple K, however, with a maximum characteristic dimension of 109 μm had many large particles.

Table 2. Observed Characteristics of Powders Analyzed by SEM

Material	Largest Particle in Picture (μm)	Smallest Particle in Picture (μm)	Estimated Median Particle Size (μm)	Appearance
Amerex	63 × 40	3 × 1.9	17 × 14	Amorphous; little dust; not much agglomeration
Ansul + 50	93 × 30	5.8 × 1.8	31 × 27.6	Little dust on particles; discrete particles, no agglomeration; lumpy particles; continuous particle size distribution
Ansul + 50C	77 × 63	9.5 × 4.6	29 × 21	Lumpy; some dust on large particles; not much agglomeration
Arm and Hammer Baking Soda	70 × 45	14 × 5	33 × 22	Extreme clumping; not much dust. Some obvious crystallinity, but generally, irregular shapes. May need more drying agent, or already be too dry so that electrostatic attraction causes clumping
DSP Desicarb Regular	114 × 90	2.4 × 2.4	20 × 14	Amorphous; lots of dust; no agglomeration
Desicarb Clone Lot BNPP-079	124 × 84	2.9 × 1.9	16 × 14	Sharp edges; some dust; much agglomeration
Kidde	95 × 66	3.9 × 2	42 × 26	Clumped; some dust; some agglomeration
BCS Lot BNWQ-241	139 × 46	0.8 × 0.6	25 × 17	Amorphous; some dust; no agglomeration
Fire-Extinguishing Al_2O_3 (Standard)	41 × 29	3 × 3	13 × 10	Little dust on surfaces of larger particles. Lumpy, rounded shapes; some rods. Few platelet particles. Fewer sharp edges than anhydrous material
Anhydrous Al_2O_3 Chemical Grade -Platelets	133 × 83 5 × 4	13.9 × 9.6 1 × 1	80 × 40	No dust; all particles consist of aggregated platelets. Sharp edges

Table 2. Observed Characteristics of Powders Analyzed by SEM (continued)

Material	Largest Particle in Picture (μm)	Smallest Particle in Picture (μm)	Estimated Median Particle Size (μm)	Appearance
MAP	152 × 164	9 × 9	23 × 16	Individual particles with little dust. Jagged, random shapes. Wide range of particle sizes. Distribution continuous except for few very large particles
Monnex[a]	44 × 34	4 × 4	17 × 11	Small particles are clumped together; large particles have dust on them. There are large, single particles; most large particles are agglomerates. Distribution appears bimodal
Purple K	81 × 59	3 × 3	23 × 13	Few median-sized particles—appears to have a bimodal distribution. Generally smooth surfaces; some dust clinging to particles

[a] Condensation product of urea and $KHCO_3$ with 15% excess of $KHCO_3$.

The data in Tables A-1 to A-13 were examined, and the characteristic dimensions of the largest particle, the average size particle, and the median size particle are presented in Table 3.

The powder with the smallest average characteristic dimension was the fire-extinguishing grade of aluminum oxide. Its value was 12 μm. The only other powder with an average characteristic dimension under 20 μm was Ansul + 50C with 17 μm.

The traditional fire-extinguishing powders—MAP (31 μm), Monnex (32 μm), and Purple K (35 μm)—had larger characteristic dimensions than most of the sodium bicarbonate fire-

Figure 2. Representative SEM Photograph. Ansul + 50C 300×

Table 3. Observations and Calculations on Powders Using Optical Microscopy

Powder Type	Largest Particle Size and (Characteristic Dimension) (µm)	Average Particle Size and (Characteristic Dimension) (µm)	Median Particle Size and (Characteristic Dimension) (µm)	Agglomeration Observed	Comments
Amerex Sodium Bicarbonate	74 × 74 (74)	24 × 18 (21)	21 × 14 (17)	Little	Poor picture resolution
Ansul + 50	86 × 49 (65)	29 × 21 (25)	26 × 19 (22)	None	
Ansul + 50C	67 × 42 (53)	21 × 14 (17)	19 × 12 (15)	None	
Arm and Hammer Baking Soda[a]	146 × 56 (90)	58 × 31 (42)	51 × 21 (38)	Some	As many large particles as small particles
Desicarb Regular	85 × 58 (70)	30 × 20 (24)	26 × 15 (20)	Little	
DXP Desicarb Clone	90 × 70 (79)	26 × 18 (22)	20 × 14 (17)	Almost none	Small sample size
Kidde Sodium Bicarbonate	46 × 32 (38)	28 × 20 (23)	23 × 16 (19)	None	Small sample size
BSC Siliconized Sodium Bicarbonate	260 × 67 (132)	43 × 24 (32)	37 × 26 (31)	None	
Al_2O_3, Fire-Extinguishing Grade	56 × 37 (46)	15 × 10 (12)	12 × 9 (10)	May be high	Irregularly shaped particles—clumping could be high
Al_2O_3, Anhydrous	88 × 60 (73)	44 × 34 (39)	44 × 36 (40)	Little	Particles appear "hairy"—may be clumps of small particles

[a] Sodium Bicarbonate.

Table 3. Observations and Calculations on Powders Using Optical Microscopy (continued)

Powder Type	Largest Particle Size and (Characteristic Dimension) (μm)	Average Particle Size and (Characteristic Dimension) (μm)	Median Particle Size and (Characteristic Dimension) (μm)	Agglomeration Observed	Comments
MAP	108 × 84 (95)	35 × 27 (31)	28 × 23 (25)	None	Several larger particles on slide, but not at any of the five positions
Monnex	142 × 46 (81)	38 × 27 (32)	27 × 19 (23)	None	Small number of particles—may not represent true conditions
Purple K	225 × 53 (109)	47 × 26 (35)	37 × 21 (28)	Little	Almost as many large particles as small particles

[a] Sodium Bicarbonate.

extinguishing powders. All the sodium bicarbonate powders except the BCS (32 μm) had average characteristic dimensions of 25 μm or less.

As would probably be expected, the Arm and Hammer Baking Soda (sodium bicarbonate) and the anhydrous aluminum oxide had relatively large average characteristic dimensions of 42 μm and 39 μm, respectively. Small particle size is not a requirement for these powders.

4. Discussion

Neither optical nor SEM techniques provide the "better" data; they complement each other. The SEM photos yield a better view of surface texture than can be seen on the optical photos. Yet, there is a good chance the operator's attention will be drawn to interesting parts of the field of view of the

Figure 3. Representative Optical Microscopy Photograph.

cathode ray tube. Thus, the SEM results may not be truly representative of the powder, since there is operator input in deciding what to emphasize.

It was relatively easy to make the optical data free of bias by observations of predetermined sections of the microscope slides. This approach was not true of the SEM data.

An advantage of the optical analysis was a limited number of particles above dust size. This allowed measurements of every particle (excluding dust). In general, there was no overlap of particles on the slides, in contrast to a great deal of overlap of particles in the SEM photos.

Table 4 is a size comparison of the median particles as determined from SEM and optical microscopy. The individual size comparisons of the 13 powders range from 9% to 74% difference, with an average difference of 32%. The median particle size from the optical technique was mathematically calculated, while the median particle from the SEM technique was chosen by the operator, and then measured. It was found to be quite difficult to select the median particles from the SEM photos since there were many overlapping particles in the field of view that had been selected for analysis. In addition, the operator's judgment was used in selecting the sample region to be evaluated. Therefore, the median particle sizes obtained using the optical technique were considered to be more accurate than the sizes estimated using the SEM. Because these differences are not large factors, either technique may be used to provide reasonable estimates; however, the optical technique is favored in this instance for size measurements only.

The fire-extinguishing effectiveness of the MPA, Monnex, and Purple K powders might be enhanced if their average characteristic dimensions were as small as that of most of the sodium bicarbonate fire-extinguishing powders. There is evidence (Ewing 1984) that smaller particles are more effective than larger ones for extinguishing fires. Yet there may well be a minimum particle size, below which effectiveness does not increase. This effect is presumably a factor of residence time of the particle in the flame. The size of the fire is obviously important in determining the minimum particle size. Tests should be conducted against representative fires to determine the minimum particle size of extinguishing powder for a given application.

Table 4. SEM vs. Optical Microscopy (Median Particle Size [μm])

Powder Type	SEM	Optical	Δ	%
Amerex Sodium Bicarbonate	17	15.4	+1.6	9
Ansul + 50	22	29.25	−7.25	33
Ansul + 50C	15	24.7	−9.7	65
Arm and Hammer Baking Soda	38	26.9	+11.1	29
Desicarb Regular	20	16.7	+3.7	18
DXP Desicarb Clone	17	15.0	+2.0	12
Kidde Sodium Bicarbonate	19	33.0	−14.0	74
BSC Siliconized Sodium Bicarbonate	31	20.6	+10.4	32
Aluminum Oxide, Fire-Extinguishing Grade	10	11.4	−1.4	14
Aluminum Oxide, Anhydrous	40	55.6	−15.6	39
MAP	25	19.2	+5.8	23
Monnex	23	13.7	+9.3	40
Purple K	28	19.2	+8.8	31
			$\sum = +4.75$	<%> = 32

It is possible in the case of Monnex that what was observed on the optical photos was a small number of clumps of particles. If true, these clumps might easily break up upon activation of a fire extinguisher. It was noted, by examining Material Safety Data Sheets (MDSDs), that Ansul + 50 contains double the amount of drying agents that Monnex has. An increase in the amount of drying agent may prevent clumping of the Monnex. This should also be tested.

The fire-extinguishing grade of aluminum oxide with the smallest average characteristic dimension of 12 μm is used in powder panels. In this application, the powder is released at the fuel source, which is the fire site. Thus, the smallest particles are not required to travel through the air from a pressurized extinguisher to the fire site. Large aerodynamic drag on small particles is not a problem when powder panels are used. However, when fire-extinguishing particles are released from a pressurized extinguisher and must travel through several feet of air to the fire site, aerodynamic drag is important. The optimal size of the particles is a function of both the aerodynamic drag and the surface area presented to the fire. This value of the average characteristic dimension will have to be determined for individual applications.

5. Conclusions and Recommendations

We are not recommending which fire-extinguishing powder to use because we have not tested the fire-extinguishing effectiveness of these powders. However, based upon our observations of the various properties of these powders (e.g., particle size and distribution, appearance, texture, and degree of agglomeration), the following conclusions were drawn.

(1) All of the sodium bicarbonate fire-extinguishing powders, with the possible exception of the BSC siliconized sodium bicarbonate, are similar enough in particle size that particle size should not be an issue.

(2) The new sodium bicarbonate powders that are intended to be dispensed from pressurized cylinders have median characteristic dimensions of 25 µm or less. This size is smaller than that of commonly used fire-extinguishing agents (Monnex, Purple K, and MAP).

(3) Small (25 µm or less) median characteristic dimensions are being used for sodium bicarbonate fire-extinguishing agents. The effectiveness of these powders should be tested in variously sized fires.

(4) Large amounts (8–10%) of drying agents are being used to ensure good flow characteristics of the sodium bicarbonate powders. Tests should be conducted on other fire-extinguishing powders to determine if they could benefit from larger amounts of drying agents.

(5) The aluminum oxide used in powder panels has a very small median characteristic dimension (12 µm). A program should be carried out to determine optimum particle size vs. distance from fire site and size of fire.

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Appendix:

Tables of Data From Optical Microscopy

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Particle sizes were determined for the 13 powders that were analyzed by optical microscopy. Tables A-1 to A-13 show particle sizes for all particles above the 7-µm characteristic size, below which the particles were defined as dust.

Table A-1. Particle Size—Amerex Sodium Bicarbonate

Max. Dimension (µm)	Dimension at 90° (µm)	Calculated Area $(\mu m)^2$	Characteristic Dimension (µm)
POSITION A			
58	49	2842	53.3
60	39	2340	48.4
53	37	1961	44.3
39	37	1443	38.0
26	16	416	20.4
16	16	256	16.0
19	12	228	15.1
12	12	144	12.0
16	5	80	8.9
7	7	63	7.9
7	7	49	7.0
7	7	49	7.0
POSITION B			
74	74	5476	74.0
58	58	3364	58.0
37	23	851	29.2
32	26	832	28.8
21	14	294	17.1
23	12	276	16.6
30	9	270	16.4
19	12	228	15.1
19	12	228	15.1
19	12	228	15.1
14	12	168	13.0
12	9	108	10.4
12	7	84	9.2

Table A-1. Particle Size—Amerex Sodium Bicarbonate (continued)

Max. Dimension (μm)	Dimension at 90° (μm)	Calculated Area $(\mu m)^2$	Characteristic Dimension (μm)
POSITION C			
35	35	1225	35.0
28	28	784	28.0
23	14	322	17.9
16	16	256	16.0
21	12	252	15.9
26	9	234	15.3
16	14	224	15.0
16	14	224	15.0
POSITION D			
58	49	2842	53.3
49	37	1813	42.6
37	34	1258	35.5
44	28	1232	35.1
39	19	741	27.2
32	23	736	27.1
28	21	588	24.2
28	19	532	23.1
23	23	529	23.0
21	21	441	21.0
28	14	392	19.8
19	16	304	17.4
23	12	276	16.6
16	16	256	16.0
7	7	49	7.0
7	7	49	7.0

Table A-1. Particle Size—Amerex Sodium Bicarbonate (continued)

Max. Dimension (μm)	Dimension at 90° (μm)	Calculated Area $(\mu m)^2$	Characteristic Dimension (μm)
POSITION E			
56	56	3136	56.0
42	42	1764	42.0
53	30	1590	39.9
37	28	1036	32.2
35	26	910	30.2
30	28	840	29.0
30	28	840	29.0
37	19	703	26.5
30	23	690	26.3
37	14	518	22.8
23	21	483	22.0
21	21	441	21.0
26	16	416	20.4
28	14	392	19.8
21	16	336	18.3
16	16	256	16.0
21	12	252	15.9
26	9	234	15.3
16	14	224	15.0
16	14	224	15.0
23	9	207	14.4
23	9	207	14.4
14	14	196	14.0
23	7	161	12.7
16	9	144	12.0
12	12	144	12.0
12	12	144	12.0
12	12	144	12.0
12	9	108	10.4
12	9	108	10.4
9	9	81	9.0
9	7	63	7.9

Table A-2. Particle Size—Ansul + 50

Max. Dimension (µm)	Dimension at 90° (µm)	Calculated Area $(\mu m)^2$	Characteristic Dimension (µm)
POSITION A			
77	56	4312	65.7
86	49	4214	64.9
32	30	960	31.0
35	23	805	28.4
19	14	266	16.3
21	12	252	15.9
19	12	228	15.1
12	12	144	12.0
12	9	108	10.4
14	7	98	9.9
POSITION B			
60	37	2220	47.1
51	32	1632	40.4
35	30	1050	32.4
42	19	798	28.2
42	19	798	28.2
28	28	784	28.0
26	26	676	26.0
32	19	608	24.7
28	16	448	21.2
21	21	441	21.0
21	19	399	20.0
30	12	360	19.0
19	14	266	16.3
16	12	192	13.9
12	9	108	10.4
7	7	49	7.0
POSITION C			
72	39	2808	50.3
35	35	1225	35.0
44	23	1012	31.8
37	23	851	29.2

Table A-2. Particle Size—Ansul + 50 (continued)

Max. Dimension (μm)	Dimension at 90° (μm)	Calculated Area $(\mu m)^2$	Characteristic Dimension (μm)
POSITION C (cont'd)			
37	19	703	26.5
26	21	546	23.4
32	16	512	22.6
32	16	512	22.6
26	19	494	22.2
23	21	483	22.0
23	21	483	22.0
21	21	441	21.0
12	12	144	12.0
9	7	63	7.9
9	7	63	7.9
7	7	49	7.0
7	7	49	7.0
POSITION D			
35	25	1225	35.0
14	14	196	14.0
19	9	171	13.1
19	9	171	13.1
9	5	45	6.7
POSITION E			
56	56	3136	56.0
70	44	3080	55.5
49	39	1911	43.7
46	30	1380	37.1
37	32	1184	34.4
39	28	1092	33.0
32	32	1024	32.0
42	23	966	31.1
30	30	900	30.0
28	26	728	27.0

Table A-2. Particle Size—Ansul + 50 (continued)

Max. Dimension (μm)	Dimension at 90° (μm)	Calculated Area $(\mu m)^2$	Characteristic Dimension (μm)
POSITION E (cont'd)			
26	19	494	22.2
21	21	441	21.0
23	16	368	19.2
19	14	266	16.3
16	16	256	16.0
19	12	228	15.1
16	14	224	15.0
16	7	112	10.6
9	9	81	9.0
7	7	49	7.0

Table A-3. Particle Size—Ansul + 50C

Max. Dimension (μm)	Dimension at 90° (μm)	Calculated Area $(\mu m)^2$	Characteristic Dimension (μm)
POSITION A			
32	26	832	28.8
30	26	780	27.9
19	14	166	16.3
16	12	192	13.8
21	9	189	13.7
14	7	98	9.9
14	7	98	9.9
12	7	84	9.2
POSITION B			
39	35	1365	36.9
23	19	437	20.9
21	16	336	18.3
23	12	276	16.6
14	14	196	14.0

Table A-3. Particle Size—Ansul + 50C (continued)

Max. Dimension (μm)	Dimension at 90° (μm)	Calculated Area $(\mu m)^2$	Characteristic Dimension (μm)
POSITION B (cont'd)			
16	12	192	13.9
16	12	192	13.9
14	12	168	13.0
14	12	168	13.0
21	7	147	12.1
16	9	144	12.0
9	7	63	7.9
POSITION C			
42	23	966	31.1
44	19	836	28.9
30	26	780	27.9
23	14	322	17.9
14	7	98	9.9
9	7	63	7.9
POSITION D			
67	42	2814	53.0
67	42	2814	53.0
30	21	630	25.1
28	19	532	23.1
21	19	399	20.0
7	7	49	7.0
7	7	49	7.0
POSITION E			
28	26	728	27.0
28	16	448	21.2
23	19	437	20.9
30	14	420	20.5
28	14	392	19.8
23	14	322	17.9
19	16	304	17.4
19	14	266	16.3
21	12	256	15.9

Table A-3. Particle Size—Ansul + 50C (continued)

Max. Dimension (μm)	Dimension at 90° (μm)	Calculated Area $(\mu m)^2$	Characteristic Dimension (μm)
POSITION E (cont'd)			
28	7	196	14.0
14	14	196	14.0
19	9	171	13.1
14	9	126	11.2
12	9	108	10.4
9	9	81	9.0
9	9	81	9.0
14	5	70	8.4
9	7	63	7.9
9	7	63	7.9
9	7	63	7.9

Table A-4. Particle Size—Arm and Hammer Sodium Bicarbonate

Max. Dimension (μm)	Dimension at 90° (μm)	Calculated Area $(\mu m)^2$	Characteristic Dimension (μm)
POSITION A			
74	44	3256	57.1
65	19	1235	35.1
POSITION B			
111	26	2886	53.7
POSITION C			
116	56	6728	82.0
93	65	6045	77.7
26	21	546	23.4
26	19	494	22.2
23	16	368	19.2
14	14	196	14.0
POSITION D			
146	56	8176	90.4
72	37	2664	51.6
65	37	2405	49.0
37	23	851	29.2
51	14	714	26.7
30	21	630	25.1
37	16	592	24.3
28	16	448	21.2
21	21	441	21.0
POSITION E			
70	65	4450	67.5

Table A-5. Particle Size—Desicarb Regular

Max. Dimension (μm)	Dimension at 90° (μm)	Calculated Area $(\mu m)^2$	Characteristic Dimension (μm)
POSITION A			
26	26	676	26.0
POSITION B			
64	44	2816	53.1
26	26	676	26.0
28	12	336	18.3
16	9	144	12.0
16	7	112	10.6
7	7	49	7.0
POSITION C			
53	19	1007	31.8
37	23	851	29.2
POSITION D			
60	46	2760	56.6
30	28	840	29.0
14	9	126	11.2
16	7	112	10.6
9	9	81	9.0
7	7	49	7.0
POSITION E			
85	58	4930	70.2
48	23	1536	39.2
28	19	532	23.1
30	14	420	20.5
26	16	416	20.4
26	14	364	19.1
16	9	144	12.0

Table A-6. Particle Size—Desicarb Clone

Max. Dimension (µm)	Dimension at 90° (µm)	Calculated Area (µm)^2	Characteristic Dimension (µm)
POSITION A			
51	37	1883	43.4
32	26	832	28.8
32	19	608	24.7
26	19	494	22.2
23	19	437	20.9
26	16	416	20.4
23	16	368	19.2
30	12	360	19.0
19	196	361	19.0
23	14	322	17.9
16	16	256	16.0
16	16	256	16.0
16	12	192	13.9
16	12	192	13.9
14	12	168	13.0
12	12	144	12.0
12	9	108	10.4
9	9	81	9.0
POSITION B			
72	56	4032	64.5
37	23	851	29.2
19	12	228	15.1
23	9	207	14.4
14	14	196	14.0
9	9	81	9.0
POSITION C			
30	30	900	30.0
19	19	361	19.0
26	12	312	17.7
24	9	306	17.5
16	12	192	13.9
12	12	144	12.0

Table A-6. Particle Size—Desicarb Clone (continued)

Max. Dimension (μm)	Dimension at 90° (μm)	Calculated Area $(\mu m)^2$	Characteristic Dimension (μm)
POSITION C (cont'd)			
14	9	126	11.2
16	5	80	8.9
POSITION D			
90	70	6300	79.4
60	28	1680	41.0
58	12	696	26.4
28	23	644	25.4
28	23	644	25.4
23	21	483	22.0
21	12	252	15.9
16	12	192	13.9
POSITION E			
32	19	608	24.7
19	14	266	16.3
19	14	266	16.3
16	12	192	13.9
12	9	108	10.4
12	9	108	10.4

Table A-7. Particle Size—Kidde Sodium Bicarbonate

Max. Dimension (μm)	Dimension at 90° (μm)	Calculated Area $(\mu m)^2$	Characteristic Dimension (μm)
POSITION A			
53	39	2067	45.5
44	26	1144	33.8
35	26	910	30.2
30	21	630	25.1
21	19	399	20.0

Table A-7. Particle Size—Kidde Sodium Bicarbonate (continued)

Max. Dimension (μm)	Dimension at 90° (μm)	Calculated Area $(\mu m)^2$	Characteristic Dimension (μm)
POSITION A (cont'd)			
23	14	322	17.9
21	14	294	17.1
19	12	228	15.1
19	7	133	11.5
9	9	81	9.0
POSITION B			
56	39	2184	46.7
35	28	980	31.7
16	16	256	16.0
12	9	108	10.4
POSITION C			
32	21	672	25.9
16	12	196	13.9
POSITION D			
37	28	1036	32.2
37	23	851	29.2
23	16	368	19.2
19	14	266	16.3
16	12	192	13.9
19	9	171	13.1
12	9	108	10.4
POSITION E			
44	44	1936	44.0
46	32	1472	38.4
32	28	896	29.9
21	14	294	17.1

Table A-8. Particle Size—BCS Siliconized Sodium Bicarbonate

Max. Dimension (μm)	Dimension at 90° (μm)	Calculated Area $(\mu m)^2$	Characteristic Dimension (μm)
POSITION A			
84	32	3528	59.4
84	37	3108	55.7
67	42	2814	53.0
39	39	1521	39.0
79	19	1501	38.7
39	26	1014	31.8
30	26	780	27.9
12	7	84	9.2
POSITION B			
260	67	17420	132.0
19	12	228	15.1
POSITION C			
58	56	3248	57.0
58	46	2668	51.7
56	37	2072	45.5
46	32	1472	38.4
19	12	228	15.1
12	9	108	10.4
POSITION D			
77	51	3927	62.7
56	37	2072	45.5
37	23	851	29.2
32	23	736	27.1
16	9	144	12.0
9	9	81	9.0

Table A-8. Particle Size—BCS Siliconized Sodium Bicarbonate (continued)

Max. Dimension (μm)	Dimension at 90° (μm)	Calculated Area $(\mu m)^2$	Characteristic Dimension (μm)
POSITION E			
123	44	5412	73.6
67	39	1613	51.1
60	37	2220	47.1
51	39	1989	44.6
39	21	819	28.6
26	26	676	26.0
28	19	532	23.1
32	14	448	21.2
21	19	399	20.0
23	12	276	16.6
26	9	234	15.3
26	9	234	15.3
16	12	192	13.9
12	12	144	12.0

Table A-9. Particle Size—Aluminum Oxide, Fire-Extinguishing Grade

Max. Dimension (μm)	Dimension at 90° (μm)	Calculated Area $(\mu m)^2$	Characteristic Dimension (μm)
POSITION A			
28	19	532	23.1
23	14	322	17.9
26	12	312	17.7
19	14	266	16.3
14	14	196	14.0
14	12	168	13.0
14	12	168	13.0
16	7	112	10.6
12	9	108	10.4
12	9	108	10.4
14	7	98	9.9

Table A-9. Particle Size—Aluminum Oxide, Fire-Extinguishing Grade (continued)

Max. Dimension (µm)	Dimension at 90° (µm)	Calculated Area $(\mu m)^2$	Characteristic Dimension (µm)
POSITION A (cont'd)			
12	7	84	9.2
12	7	84	9.2
9	9	81	9.0
9	9	81	9.0
16	5	80	8.9
9	7	63	7.9
9	7	63	7.9
9	7	63	7.9
9	7	63	7.9
12	5	60	7.7
7	7	49	7.0
7	7	49	7.0
7	7	49	7.0
7	7	49	7.0
7	5	35	5.9
7	5	35	5.9
7	5	35	5.9
49	30	1470	38.3
26	12	312	17.7
21	12	252	15.9
19	12	228	15.1
POSITION B			
16	9	144	12.0
14	9	126	11.2
14	9	126	11.2
12	9	108	10.4
12	9	108	10.4
12	7	84	9.2
12	7	84	9.2
12	7	84	9.2
9	9	81	9.0
9	9	81	9.0
9	7	63	7.9
9	7	63	7.9
9	7	63	7.9

Table A-9. Particle Size—Aluminum Oxide, Fire-Extinguishing Grade (continued)

Max. Dimension (μm)	Dimension at 90° (μm)	Calculated Area $(\mu m)^2$	Characteristic Dimension (μm)
POSITION B (cont'd)			
9	5	45	6.7
POSITION C			
56	37	2072	45.5
39	35	1365	36.9
23	16	368	19.2
26	14	364	19.1
21	16	336	18.3
12	12	144	12.0
14	9	126	11.2
14	9	126	11.2
14	9	126	11.2
14	7	98	9.9
19	5	95	9.7
12	7	84	9.2
12	7	84	9.2
9	9	81	9.0
9	9	81	9.0
9	7	63	7.9
9	7	63	7.9
7	7	49	7.0
7	7	49	7.0
9	5	45	6.7
POSITION D			
37	16	592	24.3
26	19	494	22.2
23	19	437	20.9
28	12	336	18.3
23	14	322	17.9
16	14	224	15.0
14	14	196	14.0
16	12	192	13.9
19	9	171	13.1

Table A-9. Particle Size—Aluminum Oxide, Fire-Extinguishing Grade (continued)

Max. Dimension (μm)	Dimension at 90° (μm)	Calculated Area $(\mu m)^2$	Characteristic Dimension (μm)
POSITION D (cont'd)			
12	12	144	12.0
12	12	144	12.0
14	9	126	11.2
14	9	126	11.2
12	9	108	10.4
12	9	108	10.4
12	9	108	10.4
14	7	98	9.9
12	7	84	9.2
12	7	84	9.2
12	7	84	9.2
12	7	84	9.2
9	9	81	9.0
9	7	63	7.9
9	7	63	7.9
9	7	63	7.9
9	7	63	7.9
9	7	63	7.9
9	7	63	7.9
9	7	63	7.9
9	7	63	7.9
12	5	60	7.7
12	5	60	7.7
7	7	49	7.0
7	7	49	7.0
7	7	49	7.0
7	7	49	7.0
7	7	49	7.0
9	5	45	6.7
POSITION E			
46	28	1288	35.9
28	21	588	24.2
26	16	416	20.4
21	14	294	17.4
23	12	276	16.6

Table A-9. Particle Size—Aluminum Oxide, Fire-Extinguishing Grade (continued)

Max. Dimension (µm)	Dimension at 90° (µm)	Calculated Area $(\mu m)^2$	Characteristic Dimension (µm)
POSITION E (cont'd)			
14	12	168	13.0
16	9	144	12.0
14	9	126	11.2
12	9	108	10.4
14	7	98	9.9
14	7	98	9.9
12	7	84	9.2
9	7	63	7.9
7	7	49	7.0

Table A-10. Particle Size—Aluminum Oxide, Anhydrous

Max. Dimension (μm)	Dimension at 90° (μm)	Calculated Area $(\mu m)^2$	Characteristic Dimension (μm)
POSITION A			
44	30	1320	36.3
12	12	144	12.0
POSITION B			
74	51	3774	61.4
49	37	1813	42.6
16	12	192	13.9
POSITION C			
88	60	5280	72.7
77	65	5005	70.7
65	53	3445	58.9
POSITION D			
58	58	3364	58.0
56	49	2744	52.4
49	35	1715	41.4
39	39	1521	39.0
28	19	532	23.0
19	12	228	15.1
16	14	224	15.0
16	12	192	13.9
14	12	168	13.0
12	9	108	10.4
POSITION E			
83	58	4814	69.4
51	46	2346	48.4
44	39	1716	41.4
37	16	592	24.3

Table A-11. Particle Size—Monoammonium Phosphate

Max. Dimension (μm)	Dimension at 90° (μm)	Calculated Area $(\mu m)^2$	Characteristic Dimension (μm)
POSITION A			
64	64	4096	64.0
63	51	3213	56.7
53	53	2809	53.0
46	27	1242	35.2
38	32	1216	34.9
35	21	735	27.0
21	7	147	12.1
14	10	140	11.8
9	7	63	7.9
POSITION B			
102	84	8568	92.6
100	35	3500	59.2
65	39	2535	50.3
53	42	2226	47.2
74	30	2220	47.1
35	28	980	31.7
28	25	700	26.5
19	16	304	17.4
14	14	196	14.0
14	12	168	13.0
9	7	63	7.9
POSITION C			
53	35	1855	43.1
46	30	1380	37.1
39	35	1365	36.9
42	32	1344	36.7
44	21	924	30.4
21	21	441	21.0
23	14	322	17.9
14	12	168	13.0
12	12	144	12.0

Table A-11. Particle Size—Monoammonium Phosphate (continued)

Max. Dimension (µm)	Dimension at 90° (µm)	Calculated Area $(\mu m)^2$	Characteristic Dimension (µm)
POSITION D			
46	23	1058	32.5
32	28	896	29.9
23	23	529	23.0
16	12	192	13.9
POSITION E			
56	46	2576	50.8
30	28	840	29.0
30	26	780	27.9
26	19	494	22.2
28	14	392	19.8
23	16	368	19.2
23	14	322	17.9
23	14	322	17.9
19	12	228	15.1

Table A-12. Particle Size—Monnex

Max. Dimension (µm)	Dimension at 90° (µm)	Calculated Area $(\mu m)^2$	Characteristic Dimension (µm)
POSITION A			
79	77	6083	78.0
58	58	3364	58.0
46	39	1794	42.4
44	26	1144	33.8
39	23	897	29.9
12	12	144	12.0

Table A-12. Particle Size—Monnex (continued)

Max. Dimension (μm)	Dimension at 90° (μm)	Calculated Area $(\mu m)^2$	Characteristic Dimension (μm)
POSITION B			
79	42	3318	57.6
56	39	2184	46.8
49	37	1813	42.6
28	19	532	23.1
26	19	492	22.2
23	19	437	20.9
16	14	224	15.0
16	12	192	13.9
POSITION C			
63	30	1890	43.5
21	12	252	15.9
14	14	196	14.0
12	12	144	12.0
POSITION D			
142	46	6532	80.8
30	30	900	30.0
21	19	399	20.0
21	14	294	15.9
19	12	228	15.1
21	7	147	12.1
POSITION E			
70	49	3430	58.7
30	28	1092	33.0
19	19	361	19.0
12	9	108	10.4

Table A-13. Particle Size—Purple K

Max. Dimension (μm)	Dimension at 90° (μm)	Calculated Area $(\mu m)^2$	Characteristic Dimension (μm)
POSITION A			
102	72	7344	85.7
77	23	1771	42.1
53	26	1378	37.1
28	23	644	25.4
26	19	494	22.2
19	12	228	15.1
19	9	171	13.1
14	7	98	9.9
POSITION B			
109	49	5341	73.1
74	44	3526	57.1
58	44	2552	50.5
46	39	1794	42.4
42	19	798	28.2
37	21	777	27.9
32	23	736	27.1
35	19	665	25.9
32	12	384	19.6
28	12	336	18.3
19	12	228	15.1
14	14	196	14.0
POSITION C			
88	58	5104	71.4
100	28	2800	52.9
56	28	1568	39.6
39	39	1521	39.0
37	23	851	29.2
21	12	252	15.9
19	12	228	15.1
21	9	189	13.7
12	12	144	12.0
16	7	112	10.6

Table A-13. Particle Size—Purple K (continued)

Max. Dimension (μm)	Dimension at 90° (μm)	Calculated Area $(\mu m)^2$	Characteristic Dimension (μm)
POSITION D			
225	53	11925	109.2
104	81	8424	91.8
79	46	3634	60.3
65	37	2405	49.0
44	37	1628	40.3
56	28	1568	39.6
30	14	420	20.5
9	9	81	9.0
POSITION E			
56	42	2352	48.5
88	23	2024	45.0
46	28	1288	35.9
42	19	798	28.2
28	21	588	24.2
25	14	350	18.7
16	14	224	15.0
16	9	144	12.0
7	7	49	7.0

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13. ABSTRACT *(Maximum 200 words)*

Powders are known to be highly efficient fire-extinguishing agents. There are powders available that, on both weight and volume bases, are more efficient than Halon 1301 as fire-extinguishing agents. A project was undertaken to examine several powders by both optical microscopy and scanning election microscopy. Much of the information from these two forms of microscopy is complementary.

The term "characteristic dimension" was defined and applied in order to rank the powders on a size basis. Eleven fire-extinguishing powders and two common commercial powders were examined by both forms of microscopy. The fire-extinguishing grade of aluminum oxide had the smallest average characteristic dimension followed by the "micronized" sodium bicarbonate samples. These sodium bicarbonate powders appeared to have very little agglomeration of the particles. The large amount of drying agent (approximately 8%) may explain this fact. In addition, most of the sodium bicarbonate powders had similar average characteristic dimensions. Therefore, it is felt that they may perform similarly as fire-extinguishing agents.

14. SUBJECT TERMS
fire extinguishing powders, sodium bicarbonate, scanning election microscopy, "characteristic dimension," optical microscopy

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